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THE STARBURST-AGN CONNECTION: THE ROLE OF YOUNG STELLAR POPULATIONS IN FUELING SUPERMASSIVE BLACK HOLES

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ABSTRACT

Tracing the star formation history in circumnuclear regions (CNRs) is a key step towards understanding the starburst-AGN connection. However, bright nuclei outshining the entire host galaxy prevent the analysis of the stellar populations of CNRs around type-I AGNs. Obscuration of the nuclei by the central torus provides an unique opportunity to study the stellar populations of AGN host galaxies. We assemble a sample of 10,848 type-II AGNs with a redshift range of $0.03 \leq z \leq 0.08$ from the Sloan Digital Sky Survey's Data Release 4, and measure the mean specific star formation rates (SSFRs) over the past 100Myr in the central $\sim 1-2\,$kpc . We find a tight correlation between the Eddington ratio (λ) of the central black hole (BH) and the mean SSFR, strongly implying that supernova explosions (SNexp) play a role in the transportation of gas to galactic centers. We outline a model for this connection by accounting for the role of SNexp in the dynamics of CNRs. In our model, the viscosity of turbulence excited by SNexp is enhanced, and thus angular momentum can be efficiently transported, driving inflows towards galactic centers. Our model explains the observed relation $\lambda \propto \mathrm{SSFR}^{1.5-2.0}$, suggesting that AGN are triggered by SNexp in CNRs.

Subject headings: black hole physics — galaxies: active — galaxies: nuclei

1. INTRODUCTION

Much attention has been given to understanding the relation between starbursts and AGN. Powerful emission from the central regions of galaxies is generally thought to originate from gravitational energy released via accretion onto supermassive BHs (Rees 1984), but, how to fuel BHs from ~kpc to pc scale remains an open question (Shlosman et al. 1990; Wada 2004). On the other hand, the presence of starbursts in CNRs has been conclusively established throughout the AGN family: quasars (Brotherton et al. 1999; Hao et al. 2005, 2008), radio galaxies (Wills et al. 2002), Seyfert galaxies (Heckman et al. 1997; Le Floch et al. 2001; Gu et al. 2001; Imanishi 2002; Imanishi et al. 2003; Davies et al. 2007; Wang et al. 2007; Watabe et al. 2008) and low luminosity AGN (Cid Fernandes et al. 2004; Gonzalez-Delgado et al. 2004). Starbursts have even been considered the energy source of AGN (Terlevichi & Melnick 1985). After intensive studies in the last 3 decades, especially with increasing evidence for the coevolution of supermassive BHs and their host galaxies (Magorrian et al. 1998; Tremaine et al. 2002), the debate of which process powers AGN emission has become a question of the connection between starbursts and AGN (e.g. the review by Heckman 2008). The coexistence of these two phenomena could simply reflect the fact that both live on the same gas-based diet, however, the nature of the starburst-AGN connection remains one of the mysteries in the evolution of galaxies.

Examining the starburst-AGN connection requires simultaneous observations of nuclei and starburst regions. Thanks to the torus obscuration, type-II AGN are the best laboratory for us to study the connection of central BHs and their host galaxies (Cid Fernandes et al. 2001). Statistical studies of large samples of galaxies in the SDSS reveal systematic trends between host properties and BH activity (Cid Fernandes et al. 2001; Kauffmann et al. 2003c, 2007; Wild et al. 2007). The higher the luminosities/Eddington ratios of AGN, the younger the ages of the stellar populations in the host bulges. All evidence from studies of type-II AGN undoubtedly indicates an intrinsic connection between star formation and AGN. However, one key puzzle remains unsolved: how to transport the gas over many orders-of-magnitude in radius to feed the BH?

In this Letter, we analyse the star formation histories in the CNRs of the host galaxies of type-II AGN, finding a strong correlation between the Eddington ratios and the mean SSFRs over the past 100Myr. The correlation explicitly implicates SNexp in driving the inflow to BHs, providing a new clue to understand the processes occurring in the CNRs. A model is proposed to explain the results with inclusion of turbulence excited by SNexp. The cosmological parameters $H_0 = 70\mathrm{kms^{-1}Mpc^{-1}}$, $\Omega_\mathrm{M} = 0.3$ and $\Omega_\Lambda = 0.7$ are used throughout the paper.

2. OBSERVATIONAL CONNECTION: SSFRS VS EDDINGTON RATIOS

2.1. *The sample*

An available sample of type-II AGN from the SDSS-Data Release 4 (Adelman-McCarthy et al. 2004) can be found from the MPA/JHU catalog[3] (Kauffmann et al. 2003c). This catalog includes those objects with Hα, [N II], [O III] and Hβ emission lines detected with S/N>3. The objects were selected to be type-II AGN according to their line ratios: $\log([\mathrm{O\,III}]/\mathrm{H}\beta) > 0.61/\{\log([\mathrm{N\,II}]/\mathrm{H}\alpha)-0.05\}+1.3$ or $\log([\mathrm{N\,II}]/\mathrm{H}\alpha) > 0.2$. Other measurements of these type-II AGN and their host galaxies required in this paper: dust extinction corrected [O III] $\lambda5007$ luminosity ($L_{[\mathrm{O\,III}]}$), stellar velocity dispersion (σ) of the bulge and dust-corrected stellar masses (M_*), are also included in the catalog. The stellar masses are estimated from $\mathrm{D}_n(4000)$ and Hδ_A by Kauffmann et al. (2003a) and the 3$''$ fiber based measurements are scaled to the total galaxy luminosity. We limit our sample to objects in the redshift range $0.03 \leq z \leq 0.08$ and with $\log M_*/M_\odot \geq 10.5$, generating a sample of 10,848 type-II AGN. The redshift limits reflect our wish to study the

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[3] The MPA/JHU catalog can be downloaded from http://www.mpa-garching.mpg.de/SDSS.

regions within bulges, taking advantage of the 3″ aperture of SDSS fibers. The mass limit is set to avoid the inclusion of disk dominated galaxies (Kauffmann et al. 2003c). The median relative errors of $L_{[\mathrm{O\,III}]}$, σ and M_* are 12%, 6% and 7% respectively.

The rich stellar absorption line spectra of these type-II AGN provide detailed information about their stellar content and dynamics. However, they make the nebular emission-line measurements difficult. Tremonti et al. (2004) designed a special-purpose code to fit the stellar absorption-lines and continua. This code parameterises the stellar populations of the host galaxies by fitting population synthesis models, and makes the emission line measurements more robust. We summarize the spirit of this code, then apply the results to study the stellar populations of type-II AGN hosts in §2.2.

In order to quantify the connection between the star formation and BH activity, we must estimate the BH masses and accretion rate of the galaxies. The BH masses can be estimated from stellar velocity dispersion by $\log\left(M_\bullet/M_\odot\right) = 8.2 + 4.02\log\left(\sigma/200\mathrm{km\ s}^{-1}\right)$ (Tremaine et al. 2002). Following the method described in Heckman et al. (2004), we correct $L_{[\mathrm{O\,III}]}$ in each AGN for the contribution from star formation. Then, given the bolometric luminosity $L_{\mathrm{Bol}} \approx 3500 L_{[\mathrm{O\,III}]}$ (Heckman et al. 2004), the Eddington ratio can be obtained by

$$\lambda = \frac{L_{\mathrm{Bol}}}{L_{\mathrm{Edd}}} \approx 0.25\, L_{41} M_7^{-1}, \tag{1}$$

where $L_{\mathrm{Edd}} = 1.38\times10^{38}\left(M_\bullet/M_\odot\right)$ ergs s^{-1} is the Eddington luminosity, $M_7 = M_\bullet/10^7 M_\odot$ and $L_{41} = L_{[\mathrm{O\,III}]}/10^{41}$ergs s^{-1}. We find that 90% of BHs have masses larger than $10^7 M_\odot$, with most between $10^7 \sim 10^8 M_\odot$. The [O III] luminosity distribution spans from 3×10^{39} to 3×10^{42}ergs s^{-1}, implying a range of bolometric luminosity from 10^{43} to 10^{46} ergs s^{-1}. The Eddington ratios are homogeneously distributed from 10^{-3} to 1, about 90% objects are in the range 10^{-2} to 0.3, indicating that the current sample covers a relatively complete range of the standard accretion disks (Shakura & Sunyaev 1973). In one word, the current sample represents an homogeneous one in the relevant parameters.

It should be mentioned that aperture effects are negligible in this work, we have verified that a sample limited to a narrower redshift range of $0.03 \sim 0.05$ produces almost the same results. The 3″ SDSS fiber aperture corresponds to a physical radius of $\sim 1-2$kpc for the galaxies in the present sample, allowing us to focus on the physical processes in the CNRs.

2.2. *Stellar population synthesis*

The continua and absorption lines of each galaxy are fitted by a stellar population model (Tremonti et al. 2004), under the basic assumption that any galaxy star formation history can be approximated as a sum of discrete bursts. The library of template spectra is composed of single stellar population models generated using the population synthesis code of BC03 (Bruzual & Charlot 2003), including models of ten different ages (0.005, 0.025, 0.1, 0.2, 0.6, 0.9, 1.4, 2.5, 5, 10Gyrs) and three metallicities ($0.2Z_\odot$, $Z_\odot$, and $2.5Z_\odot$). The template spectra are convolved to the measured stellar velocity dispersion of each SDSS galaxy, and three best fitting model spectra with fixed metallicity are constructed from a non-negative linear combination of the template spectra, with dust attenuation modeled as an additional free parameter. The metallicity which yields the minimum χ^2 is selected for the final best-fit model. The median χ^2 is 1.2 in our sample. The fitting results can be found on the SDSS-MPA webpage.

We split the sample into two bins by galaxy mass at $10^{10.8}M_\odot$. The bins have roughly equal numbers of objects and median stellar masses of $10^{10.6}M_\odot$ and $10^{11.0}M_\odot$.

In Fig. 1, we plot the fraction of different stellar populations for these two mass bins. The X-axis represents ten ages of the model stellar populations as indicated in the caption. From left to right, age increases. The coloured lines indicate different Eddington ratios. The Poisson errors on the histogram bins are negligible. We see that, at a given λ, the distribution of the fraction of stellar populations is roughly the same for the two mass bins. The fraction of young stellar populations ($\leq$ 100Myr) increases with Eddington ratio, whereas the fraction of the old populations ($\geq$ 10Gyr) decreases. The stellar populations are more dependent on the Eddington ratios than galaxy masses. At a certain λ–bin, we test the similarity of the distribution for the two mass bins. The two-sided K-S test gives a probability value greater than 97% for all the four λ–bins.

The SDSS spectra are obtained with optical fibers, therefore we can only measure the spatially-integrated stellar populations. To our knowledge, any evidence for radial gradients of stellar populations in CNRs remains controversial. In Seyfert galaxies, the CNR ring-shaped starbursts (e.g. Storchi-Bergmann et al. 1996) are found to be more powerful than the nuclear ($\sim$ 100pc) starbursts (Le Floch et al. 2001; Imanishi 2002). On the other hand, Raimann et al. (2003) use long-slit optical/near UV spectroscopy to show that there is no strong systematic radial gradient of the stellar populations on scales from nuclear regions to a few kpc for a sample of 22 type-II Seyfert galaxies. It is fortunate, however, the SDSS data do allow us to examine the primary driver of the starburst-AGN connection.

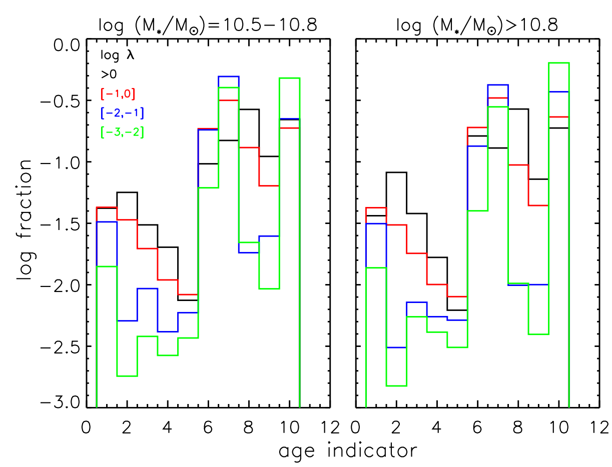

FIG. 1.— The histogram distribution of the fraction of stellar populations in type-II AGN. The X-axis represents ten ages (0.005, 0.025, 0.1, 0.2, 0.6, 0.9, 1.4, 2.5, 5, 10Gyrs) of the model stellar populations from left to right. The black, red, blue and green lines correspond to samples with different Eddington ratios. It is found that black holes with higher Eddington ratios have younger stellar populations.

2.3. *Stellar populations and BH activities*

The mean specific star formation rate over the past 100Myr can be estimated from fitting the stellar continua of the host galaxies

$$\mathrm{SSFR}(< 0.1\mathrm{Gyr}) = \frac{\mathrm{SFR}}{M_*} = \frac{\sum_{i=1}^{3} f_i}{0.1\mathrm{Gyr}}, \tag{2}$$

where f_i is the fraction of stars in each age bin and the sum is over the first three age bins i.e. over the past 100Myrs. We note that stars with masses $\sim 6.0 M_\odot$ have an main-sequence lifetime of 100 Myrs. Fig. 2 shows the relation between the mean SSFRs and the Eddington ratios of the central BHs. We find that galaxies with higher specific star formation rates in the CNRs have higher Eddington ratios of the central BHs. A linear regression shows

$$\log\lambda = (-0.73\pm 0.01) + (1.50\pm 0.01)\log \mathrm{SSFR}, \quad (3)$$

with the Pearson's correlation coefficient of 0.53 and a probability of $< 10^{-5}$ that this could be obtained by chance. This strong correlation is striking in that: 1) it directly quantifies the physical starburst-AGN connection; 2) the relation significantly deviates from the linear relation ($\lambda \propto \mathrm{SSFR}$); 3) it strengthens the case for the role of starbursts in activating BHs, and the potential role of SNexp in particular.

This correlation provides strong constraints on physical models. The accreted mass onto BHs is only a tiny fraction ($\sim 10^{-3}$) of the total gas, a simple relation like $\lambda \propto \mathrm{SSFR}^q$ is then expected if starbursts and AGN simply have the same diet, where q is unknown. A non-linear index $q \neq 1$ implies a more complicated interaction between the star formation and AGN. A higher SSFR simply means higher rates of SNexp. The present high–q value ($q > 1$) might stress a potential role of SNexp in triggering AGN. As a source of energy in the CNRs, SNexp are playing, at least, two roles: 1) heating the medium; 2) exciting turbulence via dissipation of their kinetic energy. The first may in principle lead to a certain level of star formation suppression, whereas the second role is that the excited turbulence efficiently transports angular momentum and drives inflows. AGN are then triggered. In the next section, we show how detailed processes occurring in these regions can be examined by the relation between λ and SSFR in a quantitative way.

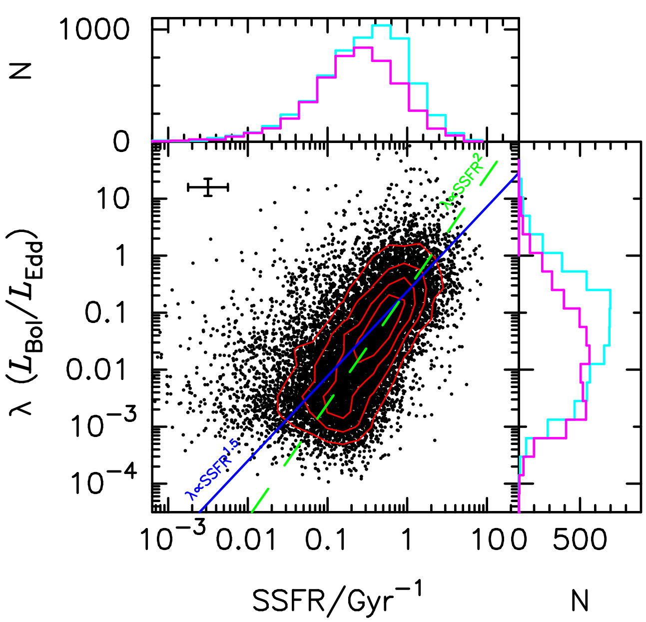

FIG. 2.— Relation between the specific star formation rates and the Eddington ratios. A simple regression, the blue line, gives $\lambda \propto \mathrm{SSFR}^{1.5}$, which is consistent with the expected relation of our theoretical model (eq. 9). The red curves are density contours. The green dashed line which passes through the contours gives $\lambda \propto \mathrm{SSFR}^{2.0}$. The magenta and cyan histograms are for mass bins of $> 10^{10.8} M_\odot$ and $\leq 10^{10.8} M_\odot$, respectively. The typical error bars are plotted in the upper-left corner, and are estimated from uncertainties in $L_{\rm [O\ III]}$, σ and stellar population fitting.

3. COMPARISON WITH THEORETICAL MODELS

As we argue in §2, the correlation shown in Fig 2. clearly unveils an intrinsic connection between the star formation and triggering of AGN. Currently, there are two main kinds of theoretical models for this connection, represented by Thompson et al. (2005, hereafter T05) and Kawakatu & Wada (2008, hereafter KW08). T05 show that the radiation pressure on dust grains is able to support the star forming regions, but in turn the star formation is controlled by a self-adjustment of the Toomre–Q parameter. This model assumes that the gaseous medium is homogeneous and stresses a balance between supernova heating and self-gravity in the star forming region. Unfortunately, this model makes the temperature of the gas so low that the commonly used α–viscosity is not strong enough to transport angular momentum since the sound speed is too slow. An external torque is needed to transport angular momentum to fuel BHs, and bar within bar instability is proposed. However, this suggestion lacks observational support. In a statistical sense, at least in the modern universe ($z < 1$), there is no evidence for the connection between star formation/AGN activity and lopsidedness (Li et al. 2008; Reichard et al. 2008).

High resolution hydrodynamical simulations show the ISM gas in the central 2 Kpc is multi-phase and not steady and homogeneous, and that the global geometry is supported by internal turbulence likely caused by SNexp (Wada & Norman 1999, 2001, 2002; Korpi et al. 1999 for ~100 pc). The vertical structure is supported by turbulence (see also Vollmer & Beckert 2003; Collin &Zahn 2008). KW08 propose a geometrically thick, clumpy and turbulence-dominated disk supported by energy from SNexp. Mass rates of accretion onto BHs may, in principle, strongly depend on star formation rates. According to eq. (12) in KW08, $\lambda \propto \mathrm{SSFR}$ is expected, which deviates from the observed relation. But the KW08 model addresses the intrinsic connection between starbursts and AGN, namely the role of SNexp in the transportation of angular momentum.

We assume that turbulence developed from SNexp is responsible for transporting angular momentum and is energized by

$$\Sigma_{\rm gas} V_{\rm tur}^2 = \eta \dot{\Sigma}_* E_{\rm SN}\left(\frac{H}{V_{\rm tur}}\right), \quad (4)$$

where $\Sigma_{\rm gas}$ is the gas surface density, $V_{\rm tur}$ the turbulence velocity, $\dot{\Sigma}_*$ the star formation rate surface density, $E_{\rm SN}$ the energy per SNexp, and H is the height of the gas disk. Here η is the conversion efficiency of the explosion energy into turbulence and highly uncertain. The accretion rate onto BHs is then given by

$$\dot{M}_\bullet = 2\pi\nu\Sigma_{\rm gas}\Omega', \quad (5)$$

where $\Omega' = d\ln\Omega(R)/d\ln R$, $\Omega = \left(GM/R^3\right)^{1/2}$, M is the total mass within radius R, and ν is the kinetic viscosity. We also assume that the turbulence causes the viscosity, namely,

$$\nu = \alpha V_{\rm tur} H, \quad (6)$$

where α is a constant. Similar to Vollmer & Beckert (2003) and Collin & Zahn (2008), we introduce the Toomre–Q as a free parameter to describe the gravitational instability

$$Q = \frac{\Omega^2}{\sqrt{2}\pi G\mathcal{C}\rho_{\rm gas}} = \frac{\sqrt{2}\Omega^2 H}{\pi G\mathcal{C}\Sigma_{\rm gas}}, \quad (7)$$

where $\mathcal{C}$ is the clumpiness of gas and $\rho_{\rm gas} = \Sigma_{\rm gas}/2H$ is used. We then have

$$\dot{M}_\bullet = c_0\alpha Q^{4/3}\Omega^{-8/3}\dot{\Sigma}_*^{(6+\beta)/3\beta}, \quad (8)$$

where the Kennicutt-Schmidt law $\dot{\Sigma}_* = \Sigma_0 \Sigma_{\rm gas}^{\beta}$ is assumed and the constant parameter $c_0 = 2^{1/3}\pi^{7/3}(\eta E_{\rm SN})^{1/3}(G\mathcal{C})^{4/3}\Sigma_0^{-2/\beta}\Omega'$. We find that the accretion is strongly correlated with the starburst rates as $\dot{M}_\bullet \propto \dot{\Sigma}_*^{1.8}$ for $\beta = 1.4$ (Kennicutt 1998). This shows a clear relation between the star formation and BH activity.

Employing the $M_* - R$ relation of $R \propto M_*^{\gamma}$, we have $\dot{\Sigma}_* \propto {\rm SFR}/R^2 = {\rm SSFR}\ M_*/R^2 = {\rm SSFR}\ M_*^{1-2\gamma}$, where we assume $M_* = f_* M$ and f_* is a constant. With the help of the Magorrian relation of $M_\bullet \propto M_*$, we have $\lambda = L_{\rm Bol}/L_{\rm Edd} \propto \dot{M}_\bullet/M_\bullet$

$$\lambda \propto M_*^{0.48\gamma-0.57} Q^{4/3} {\rm SSFR}^{1.8} = M_*^{-0.3} Q^{4/3} {\rm SSFR}^{1.8}, \qquad (9)$$

where the index is about $\gamma \approx 0.55$ (Shen et al. 2003). This relation ($\lambda \propto {\rm SSFR}^{1.8}$) agrees with the results in Fig. 2, which gives a power index in the range of $1.5 \sim 2.0$. The weak dependence of λ on M_* also follows from eq. (9) in agreement with the histogram distributions of λ for the two mass bins (the higher M_*, the lower λ from the histogram plot). We note that the strong correlation has significant scatter. We would ascribe this scatter to the free parameter Q, which numerical simulations have shown can vary widely (Wada & Norman 1999, 2002; Vollmer & Beckert 2003). It could also be due to a slight mis-match in timescales of our SSFR measure and AGN triggering. We would like to stress here that the agreement of eq. (9) with the correlation (3) results from turbulent viscosity excited by the SNexp.

The strong starburst-AGN connection provides new evidence for the coevolution of black holes and galaxies. We need a set of time-dependent equations for the interaction between AGN and starbursts in clumpy CNRs, as well as the duty cycle of quasars (Wang et al. 2006; 2008), taking into account the role of SNexp. The time-dependent model must also address the transition from blue to red galaxies driven by AGN, and incorporate a connection with downsizing evolution of galaxies (e.g. Chen et al. 2009). Observationally, more detailed information of radial gradients of stellar populations from long-slit or integral-field-unit spectrographs is expected to provide more constraints on theoretical models.

4. CONCLUSIONS

We show a striking correlation between the Eddington ratios and specific star formation rates in a large sample of type-II AGN. We find that type-II AGN in general show young stellar populations, and that the higher the fraction of young stars, the higher the Eddington ratio. This intrinsic connection strengthens the evidence for the role of SNexp in triggering BH activities. The measured correlation is consistent with a scenario in which turbulence excited by SNexp is responsible for the transportation of gas to the central AGN.

Future studies on the starburst-AGN connection are needed using high quality data to study the correlations between λ and SSFR for different classes of galaxies in terms of their morphologies and colors. This will give stronger constraints on the details of AGN triggering.

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